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6. AUTHORS Yingbo Hua				5d. PROJECT NUMBER	
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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT We have built a testbed for full-duplex radio with which we can control and process time-domain waveforms in real time. We have developed new methods for radio self-interference cancellation that are robust to transmission noise and hardware imperfections. These methods include new architectures of all-analog radio self-interference cancellation and online tuning methods. We have investigated the performance limits of all-analog radio interference cancellation subject to random interference channel instead of just some fixed scenarios. We have					
15. SUBJECT TERMS full-duplex radio, simultaneous transmission and reception					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Yingbo Hua
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 951-827-2853

## Report Title

Feasibility of Full-Duplex Radio

### ABSTRACT

We have built a testbed for full-duplex radio with which we can control and process time-domain waveforms in real time. We have developed new methods for radio self-interference cancellation that are robust to transmission noise and hardware imperfections. These methods include new architectures of all-analog radio self-interference cancellation and online tuning methods. We have investigated the performance limits of all-analog radio interference cancellation subject to random interference channel instead of just some fixed scenarios. We have developed a method to handle IQ imbalances effectively. We have analyzed the performance of a radio capable of both full-duplex and half-duplex, and obtained a trade-off relationship between full-duplex and half-duplex in the presence of residual self-interference. This project has enabled us to identify the key problems in radio self-interference cancellation and consequently to develop a new and better approach which we will continue to investigate.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
06/20/2013	1.00 Yingbo Hua, , Ping Liang, , Yiming Ma, , Ali Cagatay Cirik, and , Qian Gao. A Method for Broadband Full-Duplex MIMO Radio, IEEE Signal Processing Letters, (12 2012): 793. doi:
<b>TOTAL:</b>	<b>1</b>

**Number of Papers published in peer-reviewed journals:**

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
<b>TOTAL:</b>	

**Number of Papers published in non peer-reviewed journals:**

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**(c) Presentations**

<b>Number of Presentations:</b>	0.00
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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
1	1
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**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**(d) Manuscripts**

<u>Received</u>	<u>Paper</u>
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06/20/2013	2.00	Yingbo Hua, , Yiming Ma, , Ping Liang, and , Ali Cirik. Breaking the Barrier of Transmission Noise in Full-Duplex Radio, Milcom (05 2013)
06/28/2013	3.00	Ali Cagatay Cirik, Yue Rong, Yingbo Hua. Achievable Rates of Full-Duplex MIMO Radios in Fast Fading Channels with Imperfect Channel Estimation, IEEE TRANSACTIONS ON Signal Processing (05 2013)
07/22/2013	4.00	Yiming Ma, Ping Liang, Yingbo Hua. An Experimental Study of Broadband Radio Interference Cancellation, IEEE Radio and Wireless Symposium (07 2013)
07/22/2013	5.00	Yingbo Hua, Yifan Li. Radio Interference Cancellation with IQ Imbalance, IEEE Radio and Wireless Symposium (07 2013)
07/22/2013	6.00	Yingbo Hua, Armen Gholian. Limits of All-Analog Radio Interference Cancellation, IEEE Radio and Wireless Symposium (07 2013)
<b>TOTAL:</b>		<b>5</b>

Number of Manuscripts:

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### Books

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

### Patents Submitted

Two provisional patent applications:

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ALL-ANALOG RADIO INTERFERENCE CANCELATION

METHODS FOR CANCELATION OF RADIO INTERFERENCE IN WIRELESS COMMUNICATION SYSTEMS

### Patents Awarded

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### Awards

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### Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Yiming Ma	0.50	
Ali Cirik	0.50	
<b>FTE Equivalent:</b>	<b>1.00</b>	
<b>Total Number:</b>	<b>2</b>	

### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Yingbo Hua	0.00	
Ping Liang	0.00	
<b>FTE Equivalent:</b>	<b>0.00</b>	
<b>Total Number:</b>	<b>2</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: .....	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense .....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .....	0.00

### Names of Personnel receiving masters degrees

<u>NAME</u>
<b>Total Number:</b>

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**Names of personnel receiving PhDs**

<u>NAME</u>
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Total Number:
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**Names of other research staff**

<u>NAME</u>
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<u>PERCENT SUPPORTED</u>
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FTE Equivalent:
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Total Number:
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**Sub Contractors (DD882)**

**Inventions (DD882)**

**Scientific Progress**

This grant has contributed to the following papers:

Y. Ma, P. Liang and Y. Hua, "An Experimental Study of Broadband Radio Interference Cancellation", submitted 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)

Y. Hua, Y. Ma, P. Liang and A. Cirik, "Breaking the Barrier of Transmission Noise in Full-Duplex Radio," accepted for presentation at MILCOM 2013. (uploaded to ARO website)

A. Gholian and Y. Hua, "Limits of All-Analog Radio Interference Cancellation," submitted to 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)

Y. Hua and Y. Li, "Radio Interference Cancellation with IQ imbalance," submitted to 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)

A. Cirik, Y. Rong and Y. Hua, "Achievable Rates of Full-Duplex MIMO Radios in Fast Fading Channels with Imperfect Channel Estimation," submitted to IEEE Transactions on Signal Processing. (uploaded to ARO website)

### **Technology Transfer**

# Final Report

Feasibility of Full-Duplex Radio

ARO STIR Grant No. W911NF-12-1-0432

17 September 2012 to 16 June 2013

Yingbo Hua

Department of Electrical Engineering, University of California, Riverside, CA 92521

Email: yhua@ee.ucr.edu, Phone: 951-827-2853

## I. STATEMENT OF THE PROBLEM STUDIED

- Build a testbed to test a time-domain transmit beamforming method for self-interference cancellation in full-duplex radio.
- Discover the potentials and limitations of existing methods for radio self-interference cancellation.
- Develop better ideas to make full-duplex radio feasible.

## II. SUMMARY OF THE MOST IMPORTANT RESULTS

### A. Full-Duplex Radio Testbed

We have built a full-duplex radio testbed [1]. On this testbed, we have implemented the time-domain transmit beamforming method developed in [2] and performed real-time channel estimation and interference cancellation. Both the firmware and software of FPGA on the testbed have been programmed to enable us to choose, control and process broadband waveforms in real time.

With this testbed, we have discovered the issue of transmission noise which limits the performance of all transmit beamforming based methods including [8], [9] and [10]. This consequently motivated us to develop new approaches to break the barrier of transmission noise.

### B. New Methods for Radio Interference Cancellation

All approaches for radio interference cancellation can be grouped into all-digital, all-analog or hybrid. Among these approaches, the all-analog approach and some of the hybrid methods can be made robust to transmission noise [3].



The concepts we have developed in [3] will drive our next phase of this line of research. Among these concepts is that the interference cancellation channel must be driven directly by the RF signal from the transmitter and the tuning of the interference cancellation channel must be done without the exact knowledge of all transfer functions in the system.

We have investigated the limits of all-analog radio interference cancellation [4]. This work differs from all prior reports (including [11] and [12]) where a cancellation performance is based on some fixed interference environment. Also differing from prior all-analog cancellation methods is that we have developed new and more effective architectures for all-analog radio interference cancellation.

We have preliminarily developed an online algorithm for tuning all-analog cancellation channel without the exact knowledge of all transfer functions in the system [6]. This method is believed to be robust to transmission noise and hardware imperfections. We will continue this research as outlined in our new STIR proposal.

We have developed a simple and effective method for any baseband-related radio signal processing with IQ imbalance [5]. By incorporating this method, the performance of the time-domain transmit beamforming method shown in [2] has been improved substantially. This simple method should be used for all baseband-related signal processing problems with IQ imbalance.

### *C. Performance of Full-Duplex Radio*

We have also analyzed the performance of a radio capable of both half-duplex and full-duplex but with an amount of residual self-interference [7]. We have considered fast fading channels for which only estimated channel responses are available at receivers. We have established a tradeoff relationship between half-duplex and full-duplex in terms of the level of residual self-interference.

## III. PATENT AND COMMERCIALIZATION

- UCR filed a patent application related to [2].
- UCR filed two provisional patent applications related to [3], [4] and [6].
- Dr. P. Liang has started a new company for radio interference cancellation.

## REFERENCES

- [1] Y. Ma, P. Liang and Y. Hua, "An Experimental Study of Broadband Radio Interference Cancellation", submitted 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)
- [2] Y. Hua, P. Liang, Y. Ma, A. Cirik and Q. Gao, "A Method for Broadband Full-Duplex Radio", IEEE Signal Processing Letters, Dec 2012. (uploaded to ARO website)

- [3] Y. Hua, Y. Ma, P. Liang and A. Cirik, "Breaking the Barrier of Transmission Noise in Full-Duplex Radio," accepted for presentation at MILCOM 2013. (uploaded to ARO website)
- [4] A. Gholian and Y. Hua, "Limits of All-Analog Radio Interference Cancellation," submitted to 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)
- [5] Y. Hua and Y. Li, "Radio Interference Cancellation with IQ imbalance," submitted to 2014 IEEE Radio and Wireless Symposium. (uploaded to ARO website)
- [6] Y. Hua, "Online Tuning of All-Analog Radio Interference Cancellation," STIR Proposal, submitted to ARO, July 2013.
- [7] A. Cirik, Y. Rong and Y. Hua, "Achievable Rates of Full-Duplex MIMO Radios in Fast Fading Channels with Imperfect Channel Estimation," submitted to IEEE Transactions on Signal Processing. (uploaded to ARO website)
- [8] Y. Hua, An overview of beamforming and power allocation for MIMO relays, in Proc. MILCOM2010, San Jose, CA, Nov. 2010, pp. 99-104.
- [9] T. Riihonen, S. Werner, and R. Wichman, Mitigation of loopback self-interference in full-duplex MIMO relays, IEEE Trans. Signal Process., vol. 59, no. 12, Dec. 2011.
- [10] Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation" Online at arXiv.
- [11] S. Hong, J. Mehlman, S. Katti, "Picasso: Flexible RF and Spectrum Slicing", In Proc. Sigcomm 2012.
- [12] J. G. McMichael and K. E. Kolodziej, "Optimal Tuning of Analog Self- Interference Cancellers for Full-Duplex Wireless Communication," In Proc. Allerton Conference, 2012.